

# Materials Bound by Non-Chemical Forces: External Fields and the Quantum Vacuum

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**Keywords:** materials, phase diagram, floating water bridge, ferrofluids, Casimir effect, quantum vacuum, red blood cell, erythrocyte, self-assembly, nanofabrication, negative pressure

**Abstract.** We discuss materials which owe their stability to external fields. These include: 1) external electric or magnetic fields, and 2) quantum vacuum fluctuations in these fields induced by suitable boundary conditions (the Casimir effect). Instances of the first case include the floating water bridge and ferrofluids in magnetic fields. An example of the second case is taken from biology where the Casimir effect provides an explanation of the formation of stacked aggregations or “rouleaux” by negatively charged red blood cells. We show how the interplay between electrical and Casimir forces can be used to drive self-assembly of nano-structured materials, and could be generalized both as a probe of Casimir forces and as a means of manufacturing nanoscale structures. Interestingly, all the cases discussed involve the generation of the somewhat exotic negative pressures. We note that very little is known about the phase diagrams of most materials in the presence of external fields other than those represented by the macroscopic scalar quantities of pressure and temperature. Many new and unusual states of matter may yet be undiscovered.

## Introduction

It is common knowledge that the mechanical properties of a material depend on external influences, the most commonly-considered of these being pressure  $P$  and temperature  $T$ . These can be represented as scalar fields, often uniform over the material considered. Somewhat less attention has been paid to the effects of external fields and it is to this issue we now turn.

## External Electric and Magnetic Fields

In 2007 the floating water bridge [1] was rediscovered[2], generating a major wave of interest. The phenomenon is as follows: two containers with pure water are filled to the brim and placed in contact with each other. A high voltage of about 20 kV is applied via electrodes placed in the water. After some preliminary arcing, a bridge of water forms joining the two. If the beakers are pulled apart slowly, a thin rod-like piece of water - a “floating water bridge” - forms connecting the two. It can be a centimeter or more in length and has the appearance of a glass rod. A piece of thread can be pulled through it, and while it will bend somewhat, the thread can pass through without breaking the bridge. Clearly, this is water, but not as we normally know it.

The phenomenon is quite robust and can be easily replicated (with care to avoid electric shocks) using an old-fashioned colour TV to provide 25 kV, ordinary drinking glasses, and consumer grade distilled water from a pharmacy[4].

After Nature[3] dedicated a page to this mysterious phenomenon, it was shown that it in fact had quite a simple interpretation[6] - the water is held up by Maxwell stresses due to electric flux lines threading the water bridge. A simple calculation shows that the tension (negative pressure) per unit cross sectional area of the water bridge with an applied electric field  $\mathbf{E}$  is  $(\frac{\epsilon-1}{4\pi}) |\mathbf{E}|^2$  where  $\epsilon$  is the dielectric constant of water, which at DC or very low frequencies is large and around 80. There is a simple ferrofluid analog which is ferrofluid suspended between the poles of a magnet, and a simple analog known to most school children is a thread of iron filing or chain of unlinked paperclips suspended between the poles of a horseshoe magnet. The lesson to be learned from this is that an external electric or magnetic field can significantly alter the mechanical properties of a material.

The water bridge remains under intensive investigation[5]. While to a first approximation the explanation set out in [6] can explain a great deal of the statics and dynamics of the water bridge with water modelled as simple dielectric liquid, it remains an open question whether or not there are distinct phases of water appearing with different applied electric fields. The question of phase diagrams in 3 or more dimensions is largely unexplored. Of course for magnetic system, phase diagrams are routinely drawn in the temperature-magnetic field plane, but now with pressure suppressed. What new and interesting phases might be present in higher-dimensional phase diagrams? This would seem to be a very open field.

There are also clear practical implications in that the mechanical strengths of materials can be changed by external fields. Water in a floating water bridge clearly exhibits a rigidity, and indeed a negative pressure (tension) due to an applied electric field. For another simple example consider the work required to separate a soft iron rod into two pieces after a crack forms completely severing the material. Without an external magnetic field very little force is needed, while if an external magnetic field is applied along the rod, one essentially has to pull apart two facing North and South poles which attract each other – the iron is effectively made stronger by an external applied magnetic field.

## External Fields due to the Quantum Vacuum

In classical mechanics, the vacuum is simply empty space and unaffected by external fields or boundaries. Not so in quantum field theory, where there is a zero point energy  $\frac{1}{2}\hbar\omega$  for each normal mode of frequency  $\omega$ . Formally this sum is divergent and usually neglected, but the modes involved and thus the sum can be modified by boundaries. This is the basis of the Casimir effect [7] in which two parallel uncharged metal plates attract each with a force that varies as  $1/d^4$  with the distance between them. This can be seen intuitively in the following way: as the plates are moved closer together wavelengths long compared to  $d$  do not contribute to the (formally infinite) sum. Since the energy decreases as the plates are brought together, this constitutes an attractive force, due to the restructuring of field modes in the quantum vacuum. This force has been measured in the laboratory in 1958 [10] and again later [11].

In macroscopic systems, the Casimir effect is usually obscured by Coulomb-type forces falling more slowly with distance. However, as was pointed out long ago in [9], at the nanometer scale Casimir forces can become competitive with Coulomb ones.

An interesting example of this was studied in [8] which addressed the problem of the formation of stacks or “rouleaux” of erythrocytes (red blood cells) despite their carrying a negative charge which should make them repel each other. If one writes the total energy as a function of separation of the erythrocytes including a repulsive Debye-screened (considering blood as an ionic solution - basically salty water) Coulomb energy as well as an attractive Casimir energy

between dielectric plate, then with reasonable physiological parameters, one obtains a phase diagram with a phase in which rouleaux form and another in which they do not. Note that the Casimir energy also corresponds to a negative pressure between the cells, pulling them together.

Following [8], we model erythrocytes as dielectric plates of area  $A$  with surface charge density  $\sigma$  and dielectric constant  $\epsilon_1$  in a fluid of dielectric constant  $\epsilon_2$  separated by  $d \ll \sqrt{A}$ . With  $\Lambda$  the Debye screening length and  $v = c[(\epsilon_1 - \epsilon_2)/(\epsilon_1 + \epsilon_2)]^2$  the total free energy per unit area  $u$  as a function of plate separation  $d$  is[9]:

$$u(d) = \frac{\sigma^2 \Lambda}{2\epsilon_2} \left\{ e^{-d/\Lambda} - \left( \frac{\pi^2 \hbar v \sqrt{\epsilon_0 \epsilon_2}}{360 \sigma^2 \Lambda} \right) \frac{1}{d^3} \right\}. \quad (1)$$

The first term on the right describes the Coulomb repulsion between red blood cells while the second term describes the Casimir attraction between red blood cells. The relative strength of the effects can be described by the dimensionless parameter

$$a = \left( \frac{\pi^2 \hbar v \sqrt{\epsilon_0 \epsilon_2}}{360 \sigma^2 \Lambda^4} \right) = \left( \frac{\pi^2 \hbar c \sqrt{\epsilon_0 \epsilon_2}}{360 \sigma^2 \Lambda^4} \right) \left[ \frac{(\epsilon_1 - \epsilon_2)}{(\epsilon_1 + \epsilon_2)} \right]^2. \quad (2)$$

The Debye screening length  $\Lambda$  at temperature  $T$  is related to the ionization strength  $I$  via  $\Lambda^2 = \{\epsilon_2 k_B T / e^2 \tilde{I}\}$ . The ionization strength in physical units is  $\tilde{I} = \sum_a z_a^2 n_a$  where  $n_a$  is the number of ions/m<sup>3</sup> having an ionic charge  $z_a |e|$ . (In units of moles per liter, one employs the ionization strength  $I = [10^{-3} \text{meter}^3/\text{liter}](\tilde{I}/N_A)$  where Avogadro's  $N_A$  is the number of ions per mole). Fig. 2 illustrates the free energy per unit area as a function of  $d/\Lambda$  showing that a minimum only forms for sufficiently small values of  $a$ . The phase diagram is shown in Fig. 3 for a reference ionization strength  $I_0 = 0.05$  moles/liter and room temperature.

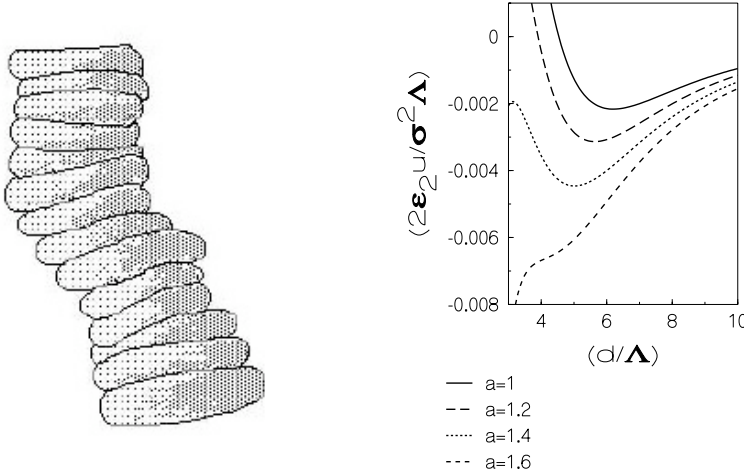


Fig. 1: Sketch of rouleaux formation by erythrocytes.

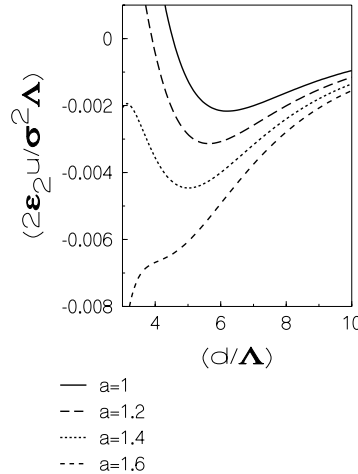


Fig. 2: Free energy per unit area as a function of separation distance.

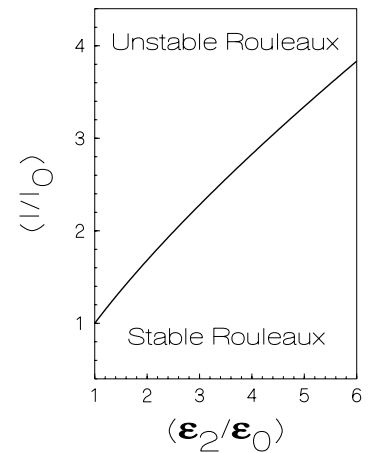


Fig. 3: Phase diagram for rouleaux formation.

At play is also a lateral Casimir force which tends to pull the plates parallel to each other to increase the negative Casimir contribution to the total energy, which increases with degree to which the plates overlap and face one another. In this case not only does the Casimir force maintain the stability of rouleaux, but in fact drives their assembly. Such effects could

form the basis not only of simpler ways to study the Casimir effect (present approaches use external mechanical forces to control plate separation), but also a variety of nanofabrication [12] techniques with possible geometries involved not needing to be that of plates. Additional external fields can be considered such as temperature or external electric fields.

Colloidal aggregation via Casimir forces has also been seen in a non-blood system[13].

## Conclusions

Material properties can be radically altered or materials bound or assembled by external classical fields or by modification of the quantum fields in the vacuum. Two examples are given in some detail: the floating water bridge in which liquid water is maintained under tension (negative pressure) by an external electric field, and the assembly and binding of rouleaux of erythrocytes by the quantum vacuum forces via the Casimir effect (which also provides a negative pressure). The field is very much open for further investigations.

## Acknowledgements

The authors would like to thank the conference organizers for a very enjoyable meeting. J. S. is partially funded by a grant from the US National Science Foundation. He would also like to thank M. Babaei for interesting discussions.

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